Investigation of Drivetrain Losses of a DP Vessel

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***Abstract*—Traditionally the efficiency of the drivetrain of a marine vessel is evaluated at rated power and speed. However, the thrust and power consumption of the thrusters are low during DP operation. In this study, the loss energy during one month is investigated. The distribution of the loss energy is shown as a function of speed and power. The results show that considerable losses are occurring at low speed and power. This motivates the need to optimize drivetrain for operational profiles, instead of optimizing them for full load operation.**

I. INTRODUCTION

Diesel electric propulsion is commonly used for supply vessels, drilling vessels, cruise vessels, and naval vessels [1]. A diesel electric propulsion system consists of prime movers (e.g., diesel engines, gas turbines) connected with generators. They are examples of the state-of-art diesel propulsion systems. The power from the generators is distributed and supplies electric propulsion motors, in addition to hotel loads, cranes, and other loads.

Diesel electric propulsion is typically used for vessels with dynamic positioning systems (DP). DP vessels uses the thrusters to counteract environmental forces and keep the position and heading fixed. Redundancy is required for equipment class 2 and 3 [2]. This is achieved by separating the power system into multiple independent subsystems, such that loss of position will not occur in the event of a single failure. As seen later in this paper, the power load on the generator and the motors are typically low (0-5% of rated power). This is a result of the design requirement for DP operation, where high thrust and power capacity is require to withstand large environmental forces during harsh weather. This complicates the design optimization problem. There are also many other aspects than losses which need to be considered during the design phase like costs, fuel consumption, and emissions. Significant savings in fuel consumption is achieved by reducing the no-load losses in operations [1].

Multiple methods are earlier presented to optimize the electric power plant for low loads. In [3], the thrust allocation method is modified to reduce the NO_X emission. Optimization methods to dimension the generator sets are presented in [4], [5], [6]. In [7], the size of diesel engine, batteries and photo voltaic panels are optimized for an oil tanker. The operation of such a system is optimized for a cruiser in [8]. A study of losses in induction machines and permanent magnet synchronous machines is presented in [9]. The article presents the losses of these machines and compare their performance as motors in marine propulsion plants. Energy analysis has been performed for multiple types of vessels, such as chemical tanker [10], fishing vessels [11], [12], and cruise vessels [13].

Studies of the efficiency of hybrid electric vehicles (HEV) are highly related to marine drive trains, as the HEV drive trains includes the same components as a diesel electric propulsion system. The losses for an HEV is evaluated in [14]. The article also models losses and estimates the loss for different driving cycles. Methods to model the efficiency electric machines in series and parallel hybrid electric vehicles as well as electric vehicles are presented in [15]. The energy efficiency of hybrid electric vehicles for different test cycles is evaluated in [16].

The power requirement and spread between high and low load for different operations is one of the design constrains, which influence the system efficiency. There is a need for a trade-off between the cost and efficiency of the installation together with compensation of the no-load losses. The efficiency evaluation is a complex question but we describe the problem in this paper from a smaller perspective concentrating on the electrical loses. The main contribution of this article is evaluations of the distribution of the losses for electric propulsion motors and generators. The motivation for the article is that the loss power at low load is small as the power is small and therefore often neglected. The aim of the article is to check if this assumption is valid.

The outline of the present article is as follows: The next section describes the time series used in this analysis and the methods used to model the losses. Results are presented in Section III, where the loss distribution is presented. These results are further discussed in Section IV, before conclusions are drawn in Section V.

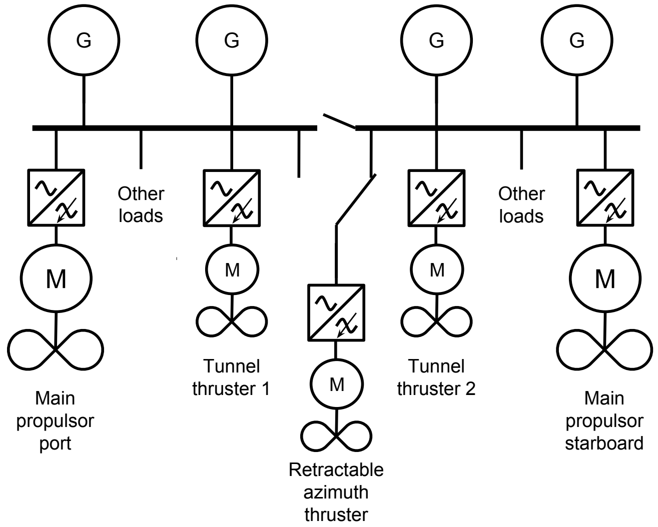

Fig. 1. Single line diagram of the vessel.

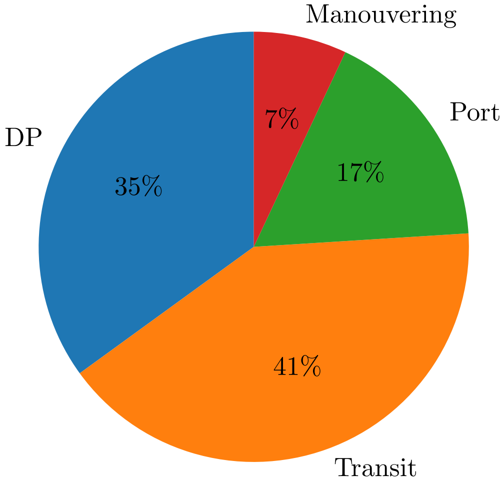

Fig. 2. Time spent in each of the operational modes.

II. METHOD

In this paper the total loss energy of a generator and a thruster drive is estimated. This is calculated by combining time series of usage of thruster for a platform supply vessel and efficiency maps of motors and generators from the lab at NTNU.

A. Vessel

The single line diagram of the vessel is shown in Figure 1. The vessel has two rotatable thrusters for main propulsion with variable pitch and speed, in addition to two tunnel thrusters and a retractable azimuth thruster. Four diesel generator sets are used to produce electric energy, connected to two switchboards in pairs. The size of the generators and motors are in order of MWs.

A time series of the operation of the vessel is used in this article. It is based on operation in the North sea in August. As shown in Figure 2, the vessel operation is divided into four modes: DP, transit, port, and maneuvering. The division of modes is mainly based on the vessel's speed and connection signals from selected components. The usage of the main propulsion motors is shown in Figure 3 as a function of both speed and power. Note that the speed is typically 45-55% at low power (0-5%). This is due to a limitation such that speed is never below a certain limit. The pitch is then reduced such that no or a small thrust is achieved. This is done to improve the dynamical performance of the thruster during DP operations. Figure 4 shows the usage of the generators as a function of power.

B. Efficiency

The efficiency of the actual equipment on-board the vessel is not available for this study. Instead, the efficiency of the equipment of NTNU's hybrid power lab is used. A single line diagram of the laboratory is shown in Figure 5. It consists of a 350 kW synchronous generator and two 200 kW induction motor. Direct current (DC) is used for distribution. The power is measured at three locations in the lab. The mechanical output power of the diesel engine is measured by combining strain gauge and shaft speed measurements. The electric output power of the generator is measured by current and voltage sensors by an Elspec instrument. The mechanical output power of the induction machine is measured by an integrated torque sensor in the eddy current brake and shaft speed measurements. These four measurements are used to measure the efficiency of the equipment. The power measurements of each side of the generator is used to estimate the efficiency of the generator. The electric power measurement and the mechanical power measurements of the brakes are used to estimate the combined efficiency of the induction motor and the frequency converter. The power is measured at multiple power levels and speeds. The combined efficiency of the induction motor and variable frequency drive is shown in Figure 6. The efficiency of the generator is shown in Figure 7.

III. RESULTS

A. Propulsion motor losses

The loss energy is calculated by:

1) For each interval (e.g., 5 – 10% power and 40 – 45% speed) the average loss power is calculated using Figure 6:

$$p_{loss}(\omega, p) = \big(1 - \eta(\omega, p)\big)p,$$

where ω is the motor speed and p is the power.

2) The energy loss is then calculated by multiplying the loss power by the time ratio from Figure 3.

$$E_{loss}(\omega, p) = p_{loss}\,(\omega, p)\, r(\omega, p),$$

where r is the ratio of the time the motor is used in the given interval.

3) The energy loss is then normalized by dividing by the total energy loss:

$$E_{loss,normalized}(\omega, p) = \frac{E_{loss}(\omega, p)}{\sum\limits_{\omega,p} E_{loss}}.$$

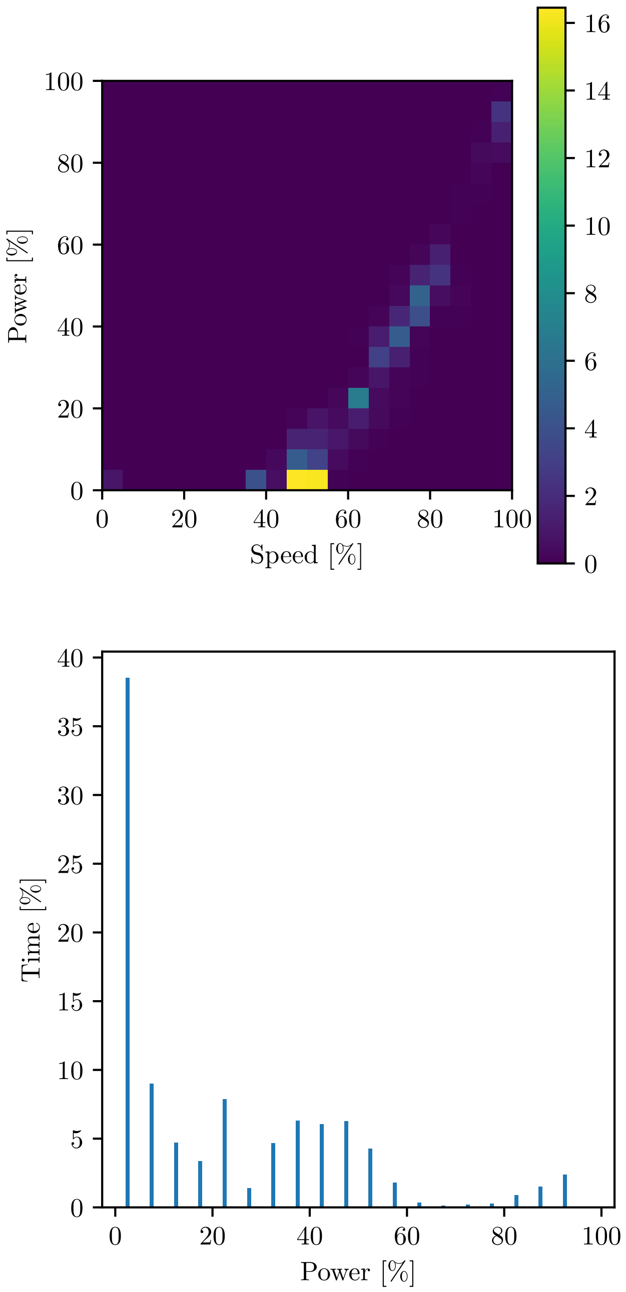

Fig. 3. Ratio of time spent at different load conditions for the motors. The upper plot shows the usage as a function of the rotational speed of the motor (x-axis) and power (y-axis). The lower plot shows the time spent (y-axis) at different power levels (x-axis).

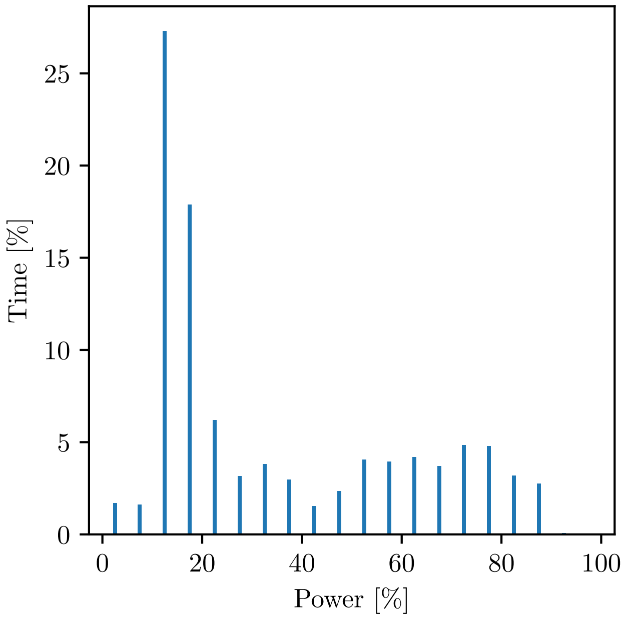

Fig. 4. Ratio of time spent at different power levels for the generator.

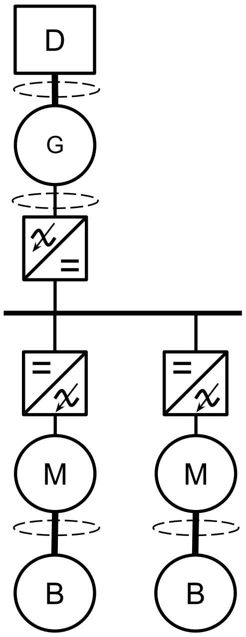

Fig. 5. Single line diagram of the lab. The lab consists of a diesel engine (D), synchronous generator (G), rectifier, DC link, inverters, induction motors (M), and eddy current brakes (B). The dashed circles are points of power measurements. Measurements of the mechanical power are done on the shaft between the diesel engine and the generator, and between the induction motors and the associated brakes. In addition is the electric power from the generator to the rectifier measured.

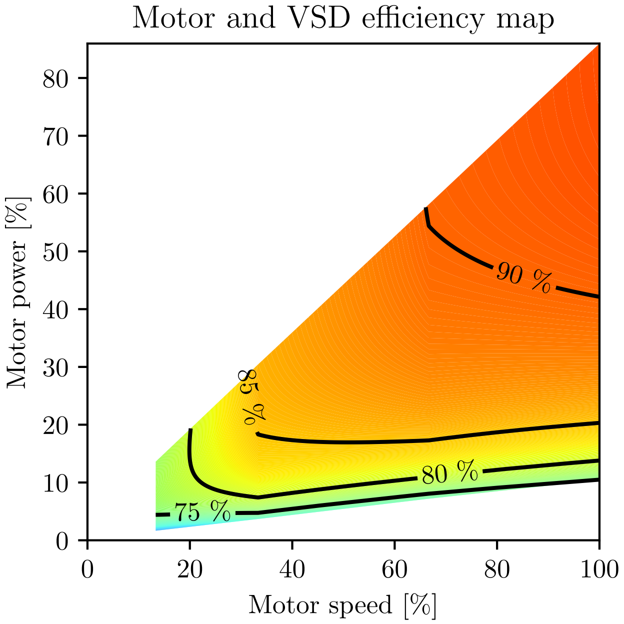

Fig. 6. The combined efficiency of the induction motor and variable frequency drive as a function of motor speed and motor power.

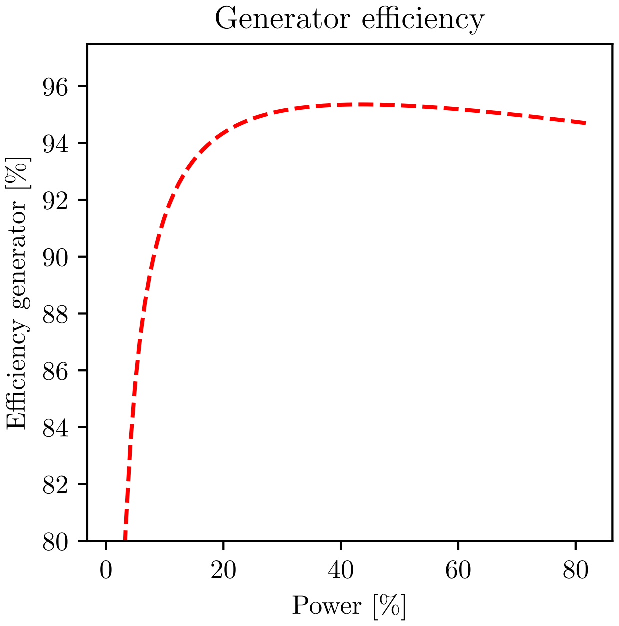

Fig. 7. The efficiency of the generator.

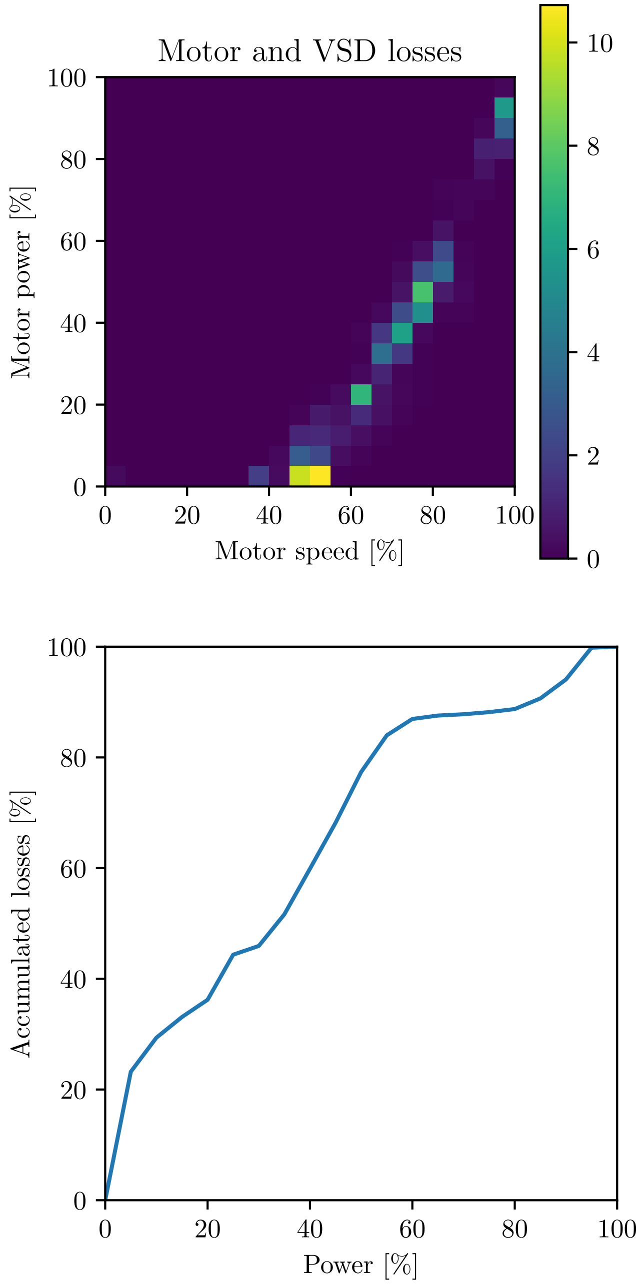

Fig. 8. Distribution of losses for variable speed drive and motor. The upper plot shows the distribution of the total loss energy. For example, 5% of the loss energy is occurring at 20 – 25% power and 60 – 65% speed. The lower figure shows the accumulated losses as a function of power.

Figure 8 shows the loss distribution for the motor and VSD. Note that 25 % of the energy loss is at 0-5% power and 90% of the energy loss is at below 60% power.

B. *Generator losses*

The total loss energy is estimated by combining Figure 4 and 7 using the same method as for the motor and VSD. The distribution of the loss energy is shown in Figure 9. For the generator, the losses are mainly at high power utilization. The

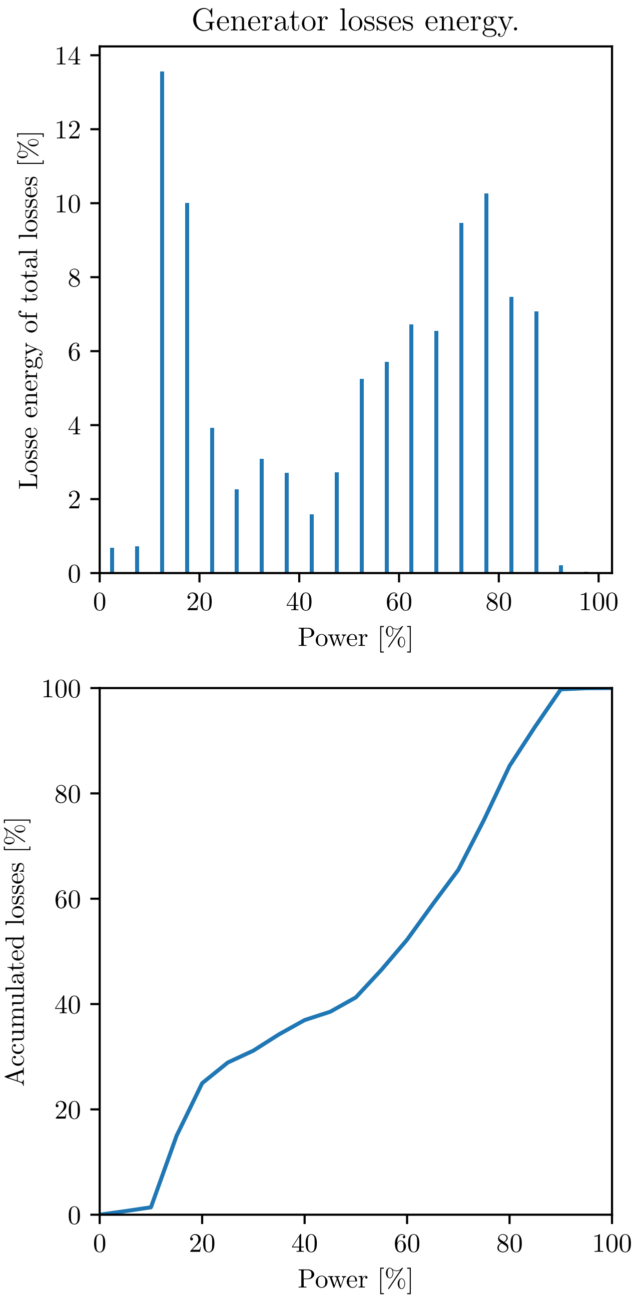

Fig. 9. Distribution of losses for the generators. The upper plot shows the distribution of the total loss energy. For example, 10% of the loss energy is occurring at 15 – 20% power. The lower figure shows the accumulated losses as a function of power.

used generator has a high efficiency above 25 %. Approximately 60% of the energy losses are at 50% power and above.

C. Efficiency

Figure 10 compares the actual efficiency with the efficiency at rated values (power and speed). The actual efficiency is the ratio between energy out and energy in to the component for the entire load profile. For the Motor and VSD the actual efficiency is lower 3.7 percentage points than the rated efficiency. This is due to the low efficiency at low loads. For the generator the actual and rated efficiency are close (difference of 0.3 percentage points). This is due to the relative constant efficiency of the generator, see Figure 7.

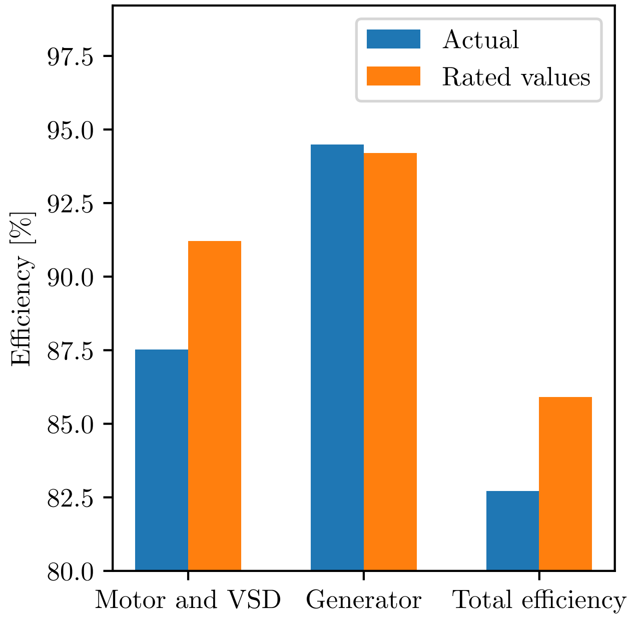

Fig. 10. Efficiency of the motor and VSD, generator, and total efficiency from generator shaft to motor shaft. The blue bars is the actual efficiency when using the load profiles, while the orange bars shows the efficiency at rated power.

IV. DISCUSSION

The losses presented in Figure 8 shows that low load losses are important. For this vessel, the motors are loaded between 0–5%, 38% of the time. Even though the loss power is small at this level due to the low power, the losses accumulates and becomes a significant part of the accumulated energy loss for the motor and VSD (25% of loss energy). The generators spend 45% of their time utilizing only 10–20% of their power rating. This contributes to 20% of the losses. This should motivate for design of equipment optimized for low loads as well as high loads.The solution for this can be for example, permanent magnet or hybrid technology. One way of increasing the system efficiency can be also a variable speed of the generator. Looking at the problem from wider perspective, the high energy loss is compensated by variable speed motor and controllable pitch propeller. The control of the vessel is then improved with lower fuel consumption. A fixed pitch propeller with variable speed would have lower losses, however then the dynamic performance of the vessel is reduced. This motivates to include losses of all main components, engines, thrusters and propellers, during total system evaluation.

It should be noted that the results are based on data from only one vessel during one-month operation. The equipment used to estimate efficiency are also rated low compared with typical equipment in platform supply vessels. Low rated equipment (here 200 kW) have typically lower efficiency at full load than high power rated equipment (multiple MWs). However, we are concerned about the distribution of the loss energy. It is independent of the efficiency as long as the ratio between low and high load losses are similar.

V. CONCLUSION

The present article presents the distribution of losses for generators and propulsion drives for a supply vessel. The results are based on measured utilization of these equipment of a platform supply vessel and efficiency maps from the equipment of NTNU marine hybrid power lab. Only load factors and operational profile is based on the logged data, so the loss factors used are not linked to the actual vessel performance. The calculated energy losses shows that the losses of a propulsion drive are mainly at low power, as more than 20 % of the loss energy is at 5% power or lower and 90 % of the loss energy is at 60 % power or lower. For the generator, 25% of the loss energy is at below 20% power and 60% of the loss energy is at 50% power or below. This shows that when optimizing marine propulsion systems using an operational profile, the actual efficiency of the machinery should be used and not the rated efficiency. Increasing the efficiency of marine propulsion systems is a wider and a more complex question because of the design challenges and requirements. One solution to improve the efficiency could be installing a few low rated components so the vessel could operate with higher efficiency and we will receive less accumulated losses. However, the idea is not a cost effective approach. Generally, there is a need for a trade-off between costs and efficiency of the installation. Looking at the topic of losses we cannot disregard the most significant losses from the mechanical components. One method, which is already implemented and shown in the paper is the control of the speed of the thruster motor and compensation of the zero pitch losses. We could clearly see from the power span from operational data that the vessel is operating with reduced speed and power from the main propulsion what reduces the zero pitch losses. At the same time, there is a capacity to maintain the position in the challenging DP operations what is one of the design criteria. The implemented speed limit in the thruster motor allow to control the vessel in a more responsive way when the thrust is not needed. We can improve the maneuverability by quickly changing the pitch of the propeller. To conclude, low losses are accumulating and as presented in the paper they are still significant. This motivate usage of new technologies, especially for a combustion engines, which run in low and non-optimal load conditions or possible improvements by use of energy storage or permanent magnet technology.

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